

10 Micron Search for Cool Companions of Nearby Stars

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ABSTRACT

We present 10 micron broadband images of the nearby stars Gleise 15, 71, 628, 699, 725A, 725B, 729, and 820A from an experiment designed to detect cool companions. The observations establish upper limits for the presence of companion objects with separations between 2 and 10 arcseconds at or below the hydrogen burning limit for Gleise 15, 699, and 729.

Subject headings: stars: low-mass, stars: planetary systems, techniques: image processing

1. Introduction

With the discovery of Gleise 229B (Nakajima, *et al.* 1995), the low mass companion to Gleise 229, it is now clear that substellar objects in the mass range one decade below the hydrogen burning limit exist in at least moderate numbers. In anticipation of a dynamical mass for Gleise 229 B under $0.08 M_{\odot}$ attention now turns toward determining the frequency, taxonomy, formation, evolution and astrophysical consequences of brown dwarfs and massive extrasolar planets.

In carrying out this program it is essential to obtain a sizeable sample of objects which can be studied in detail. A number of approaches have been proposed and are being pursued, including astrometric and velocity monitoring, coronagraphic imaging, and mid-infrared imaging of nearby stars from the ground and space. Because this is an empirical problem, a broad suite of search strategies is important. In this short paper we describe exploratory 10-micron imaging from the Palomar 5-m telescope of nearby stars. This wavelength is appropriate for a search because the blackbody peaks for companions with temperatures between 100 K and 1000 K are near this wavelength. Our experiment is formally capable of detecting objects with a flux density greater than 10 mJy in the separation range 2-10 arcseconds from the primary. While the flux limit is much shallower than can be achieved from space (eg with ISO), it probes a separation range not accessible to orbital telescopes by using the small diffraction-limited beam available to a large telescope.

Current successful methods for detecting massive extrasolar planets, i.e. radial velocity and astrometric methods, are primarily sensitive to short periods and hence small orbits of order 3 A.U. or less. The direct detection experiment explored here is of considerable interest because it is sensitive to planets in 3-50 A.U. orbits about their primaries, right in the range where gas giants planets are predicted to form (Pollack et al 1996; Boss 1965).

Models for planet formation, developed to explain our own solar system, have planets

forming via the accumulation of solid particles (dust and ices) from the size of grains to planetesimals. When rocky cores reach 10-20 earth masses, the nebular gas can accrete, forming gas giants (Pollack 1984). Given this picture, the surprising discovery of massive planets at sub-A.U. distances from their primaries has led to a view where planets undergo inward orbital migration from their birth places outside the ice condensation radius of 3-5 A.U. (Trilling et al, 1998).

A direct 10-micron search for cool companions and massive extrasolar planets is a reasonable experiment in terms of the yield per target based on the following statistics:

- 6% of solar-type stars have giant planets, $m \sin i > 0.5 M_{Jupiter}$, within 3 A.U. (Marcy and Butler, 1998). Interestingly, this cutoff would exclude our solar system.

- 2% have brown dwarfs within 5 A.U. (Mayor, 1998).

- There is a roughly 10% incidence rate of stellar companions for each decade in orbital size (Fischer and Marcy, 1992). If the incidence rate of companions is nearly mass-independent (which seems plausible given the first bullet) then there are a correspondingly large number of brown-dwarf and giant-planets.

Ultimately, several tens of stars must be observed with sufficient sensitivity to begin addressing the issues raised above. This class of experiments, 10 micron direct imaging, has the potential to quickly reach that goal.

2. Observations

We carried out our observations during the nights of 14 and 15 August 1996 (UT) with the MIRLIN camera (Ressler, *et al.* 1995) at the Cassegrain focus of the Hale 5-m telescope at Palomar Observatory. MIRLIN uses a 128×128 array detector with a 20

arcsecond field of view. The instrument manual quotes a sensitivity of $\approx 10 \text{ mJy } 1/\sqrt{\text{hour}}$ at the broadband N filter (10.2 microns) in which we observed. The weather during the observations was non-photometric, and data taking was interrupted at one point by light precipitation.

We observed 8 targets, spending on average one hour on each. We chopped and nodded to remove first and second-order sky-induced drifts. Usually the chopper throw and nod offset were 8 arcseconds (on-chip chopping and nodding), although some data was taken with larger throws and offsets to eliminate any source aliasing. Because on-chip chopping and nodding results in no off-target data at the slight loss of a small fraction of the sensitive field of view, we favor it for experiments aimed at small separations. Over the course of the observing a single object we dithered the pointing center by a few arcseconds to suppress detector artefacts. Table 1 is a journal of our observations indicating our targets, starting times, number of chop/nod cycles, and chop/nod offsets.

The instrument datasystem produces flat FITS files containing coadds at each chopper position and ancillary metadata typical of any camera experiment. The data were reduced using a collection of IDL¹ functions implementing a lightweight reduction system in about 500 lines of code.

A single observation cycle is made up of four images: two chopper coadds at two nod positions. Let the first index be the nod position and the second be the chopper position, then these four images can be called $I_{jk} = I_{11}, I_{12}, I_{21}, I_{22}$ with I_{11} and I_{12} being the chopped pair at the first nod position. The reduction starts by constructing a mask M_{jk} corresponding to each image which flags bad pixels. There are two classes of bad pixels:

¹IDL (Interactive Data Language) is a trademark of Research Systems, Inc. of Boulder, Colorado.

there is a fixed pattern where 1 of every 16 pixels produces bad data because of a problem in the electronics; the second class is composed of temporarily noisy or hot pixels determined from the data itself. If a pixel is too many standard deviations different from its neighbor it is masked out. Because the point spread function is heavily oversampled, masked pixels are replaced with the median of their neighbors to cosmetically repair the data. The repaired images, $R(I_{jk})$ are then flat-fielded using a median flat generated from the four input frames to give the flattened images $F(R(I_{jk}))$. Next we compress the images by a factor of 4 in each dimension by summing groups of 4×4 pixels and constructing a mask containing the corresponding 4×4 -summed mask values. The resulting images, $C(F(R(I_{jk})))$ are slightly undersampled with respect to the Nyquist frequency of the telescope beam and are close to optimizing the signal to noise ratio per pixel for point source detection.

The next step in the processing constructs the difference images $C_{11} - C_{12}$ and $C_{21} - C_{22}$. These difference images are themselves differenced to give $Q(C(F(R(I)))) = C_{11} - C_{12} - C_{21} + C_{22}$, which removes the sky and its first order spatial derivatives. Q and $-Q$ are now shifted and coadded so each appearance of the primary is placed at the center of the resultant map, yielding an image $S(Q(C(F(R(I))))$ where the primary is aliased 8 times. Any real source inside the chop and nod bounding box will likewise be aliased up to 8 times. This procedure is cycled through for all sets of quadruples I_{jk} comprising the set of observations for a single target. In one case both stars of a known binary were targeted. The two fields were treated separately rather than mosaicked together.

Images obtained after this reduction contain aliased sources, confusing the identification of any faint objects which may be present. A more straightforwardly interpreted image of the field is finally made by taking into account the aliasing pattern. To construct this final image, we perform a logical filtering operation $\mathcal{L}(Q)$ on the image, passing pixel values

unchanged when the signal at aliased positions deviates from the background in the proper direction for a real source, and setting all other pixels equal to zero. An image containing random noise treated in this fashion will pass a fraction $1/2^8$ pixels, or 0.4%.

We expect that by chance there will be a few pixels passed in the field away from the image of the primary, which would lead to an impermissively high false detection rate. This rate is dramatically lowered by taking advantage of the fact that a real source appears in several neighboring pixels because of the spatial sampling. In the absence of systematics, a block of four adjacent pixels in the final image virtually guarantees that a source was detected at that position. Unfortunately aliases of bright sources as well as uncalibrated instrumental and background drifts significantly reduce the significance of passed pixels to the point where each potential source must be investigated in further detail. In figure 1 we show schematically how the logical filter operates on an input coadd containing sources and their aliases to produce the output image in which the aliases are suppressed.

In setting our upper limits for detections, we use the fluxes corresponding to the brightest pixels passing the logical filter which have at least one neighbor and are not confused with aliased images of the primary. Since there are usually a few such pixels and we expect *a priori* that low luminosity companions are not too common at our sensitivity level, it is justified to use these noise excursions to set upper limits.

3. Results

For each target we generate logically filtered coadds using the procedure just described. These are reproduced in figure 2. In these images non-zero pixels formally have statistically significant positive flux, and groups of adjacent pixels would correspond to real sources in the absence of systematics. Often candidate sources are aliased known sources: for example

the image of Gleise 725 A contains an aliased image of Gleise 725 B which was passed by the logical filter, an event which has unremarkable probability. Another source of systematic error is introduced primarily by the atmosphere. Rapidly changing conditions can result in uncalibrated large-scale structure in the flat-fields, which locally biases the zero point, leading to an amplification of the noise peaks.

A real source at the projected position of an aliases will suffer strong confusion. The immediate neighborhoods of aliases are thus to first order not sampled at all. Filling in these areas would require taking data with different chopper and nod offsets to move the sky positions of aliases around. We did obtain a small amount of data in this mode, and we will improve future experiments by splitting the time on each target into two sets, each with different sampling geometries.

Table 2 summarizes the observational results. For each target we note its name; its estimated N-band flux density based either on its IRAS 12-micron flux density or, for the case of Gleise 725 B, calibrated against a companion whose 12-micron flux density is known; the measured rms noise in the coadded (but not logically filtered) image; and the detection limit based on the brightest noise pixel which also has a neighbor present in the image passing the logical filter. All primaries are well detected. No new objects are present at the 95% confidence level. Unfortunately the depth of coverage is not uniform because atmospheric conditions during the observations caused the transparency to vary by a factor of three and the background to vary by a factor of fifteen.

4. Discussion

The goal of our search was to apply mid-infrared imaging techniques to the problem of detecting substellar companions to nearby stars. This modest goal was met in spite of

weather conditions preventing us from achieving high sensitivity. None-the-less, our data place some constraints on the presence of substellar companions of the target stars.

Ground-based 10-micron searches for faint companions are competitive with space experiments at close separations, inside a few times the diffraction beam of the space experiments, i.e. within 10-15 arcseconds. At greater separations the far lower backgrounds achievable with a space experiment yield sensitivities of a few mJy or less. Reaching 10 mJy limits within 10-15 arcseconds of stars from the ground requires large telescopes and hours of integration time per target.

These fiducials define the parameter space of the experiment. At a distance of 5 pc, 10 arcseconds is 50 AU, and orbital periods for companions at these semimajor axes are millenia for K and M star primaries. A 10 mJy substellar object with a radius $0.1 R_{\odot}$ has a brightness temperature of 1160 K when at 5 pc. This sensitivity is achievable in good weather with MIRLIN in about 1 hour of telescope time. Our experiment does set interesting upper limits to the brightness temperature of any low mass companions in the surveyed range of projected separations for three of the targets.

In interpreting our results we use the brown dwarf cooling curves computed by Nelson, Rappaport and Joss (1993, NRJ). Table 3 transforms the observational results into useful physical parameters in the context of brown dwarfs and low mass companions to stars: the range of projected separations sampled by the experiment on each star; the brightness temperature upper limit obtained from the flux upper limit following the assumption of a pure black-body spectrum and taking a source size of $0.1 R_{\odot}$; and lastly, the corresponding mass upper limit for non-stellar objects using the evolutionary tracks in the (T_{eff} , age) plane. In setting these upper limit bars, we use age indicators from Leggett’s (1992) compilation translated as: young - older than 10^8 years; old: older than 5×10^{10} years and force $T_{eff} = T_{brightness}$, which could be in error by a factor of order unity. The smallest

upper limit we set is $0.045 M_{\odot}$ for Gleise 729. Figure 3 shows the NRJ cooling curves with our three interesting nondetections overlaid.

Our sample size of three objects within the region of applicability for the brown dwarf cooling function is not sufficiently large to make any significant global statistical statements. Instead, they show that this class of experiments begins to probe an interesting region of parameter space. A heuristic rule for obtaining the fraction of stars which have binary companions in a given decade of projected separations is that roughly 10% do (see, for example, Fischer and Marcy 1992). If this heuristic persists into the substellar mass regime then we expect about 7% of the surveyed stars to have companions in the sampled separation range with any mass less than the primary's. Our experiment simply is too small to begin to measure the abundance of substellar companions by a factor of ten or so; it is even too small to rule out the possibility that 80% of all nearby stars have substellar companions in the sample range of projected separations and brightness temperatures at the 99% confidence level.

This kind of experiment is clearly feasible, and if improved has the potential to advance the state of knowledge regarding low mass companions to stars. There are a number of directions to go in improving the experiment:

- More targets.
- Improved targets.
- Larger sampled range of projected separations.
- Higher sensitivity.

Extending to more targets, eventually the target list comprises the entire set of nearby stars with more distant stars so far away that their companions become very difficult to detect because of their faintness. Improving the target list by choosing young stars biases

the sample toward objects whose low mass companions are on the high luminosity left hand side of the brown dwarf cooling curve and hence brighter and easier to detect. Going to a larger sampled range of projected separations increases the detection rate since companions are likely to exist over a large range of semimajor axes given that stellar companions do. Finally, achieving higher sensitivity (ours is nothing special!) improves the yield per target by bringing older and lower mass companions into the observable region of parameter space.

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Fig. 1.— FIGURE1

The logical filtering operation. An 8-point filter is passed over the image (left), whose output (right) is zero if the deviations from the mean background are not all in the same direction as that expected for a source aliased to the 8 points in the coadd. Otherwise the output is the pixel value at zero-lag. This filter suppresses source aliases.

Fig. 2.— FIGURE2

Logically filtered on-chip chop and nod coadds of the eight target stars made with MIRLIN. From top to botton, left to right: Gleise 15, 71, 628, 699, 725A, 725B, 729, 820A. Each image is about 10 arcseconds on a side. We set the detection upper limits to be the magnitude of the strongest off-primary non-aliased pixel with a neighboring non-zero pixel. A strong alias of the primary is present in the lower right corner of the Gleise 628 filtered image. Likewise, the apparantly significant object at 4-o-clock in the Gleise 725A image is an alias of Gleise 725B, which appears in the southern nod frames of the Gleise 725A observations.

Fig. 3.— FIGURE3

The allowed regions for companion masses plotted with the NRJ brown dwarf cooling curves on the (T_{eff}, age) plane. The tops of the allowed regions correspond to the upper limit flux values, and their left ends are determined by adopting lower age limits of 10^8 , 5×10^9 and 10^{10} years for Gleise 729, 15, and 699 respectively. All the other stars have effective temperature upper limits in the range 4200 to 22000 K (for radii of $0.1 R_{\odot}$), which would imply stellar, not substellar masses of any detections. This figure was adapted from one appearing in NRJ with the kind permission of the authors.

Table 1. Journal of Observations

Star Name	Start Time 1997 August UT	Chop/Nod Sets	Spacing "	Integration Time seconds
Gleise 15	14 10:54	19	8 and 10	2228
Gleise 71	15 11:31	2	8	240
Gleise 628	14 03:58	17	8	2040
Gleise 699	15 03:18	21	8	2520
Gleise 725A	14 06:00	9	8	1080
Gleise 725B	14 06:34	8	8	960
Gleise 729	15 05:07	18	8	2160
Gleise 820A	15 07:19	14	8	1680

Table 2. Observational Results

Star Name	N-band flux density	1σ noise	Upper Limit
	Jy	mJy	mJy
Gleise 15	4.5	10	40
Gleise 71	23.7	211	670
Gleise 628	2.0	43	165
Gleise 699	2.8	23	57
Gleise 725A	3.9	60	161
Gleise 725B	2.4	74	181
Gleise 729	1.4	48	78
Gleise 820A	17.0	36	125

Table 3. Brightness Temperature and Mass Limits for Low Mass Companions

Star Name	Projected Separation	Brightness Temperature	Mass
	AU	Upper Limit K	Upper Limit M_{\odot}
Gleise 15	9 - 36	1800	0.083-0.084
Gleise 71	9 - 37	22000	---
Gleise 628	9 - 43	7400	---
Gleise 699	4 - 18	1000	0.070-0.080
Gleise 725A	7 - 35	5400	---
Gleise 725B	7 - 35	6300	---
Gleise 729	6 - 30	2300	0.045-0.086
Gleise 820A	7 - 35	4300	---





